



For RHIC Retreat

RHIC Spin Collaboration Meeting

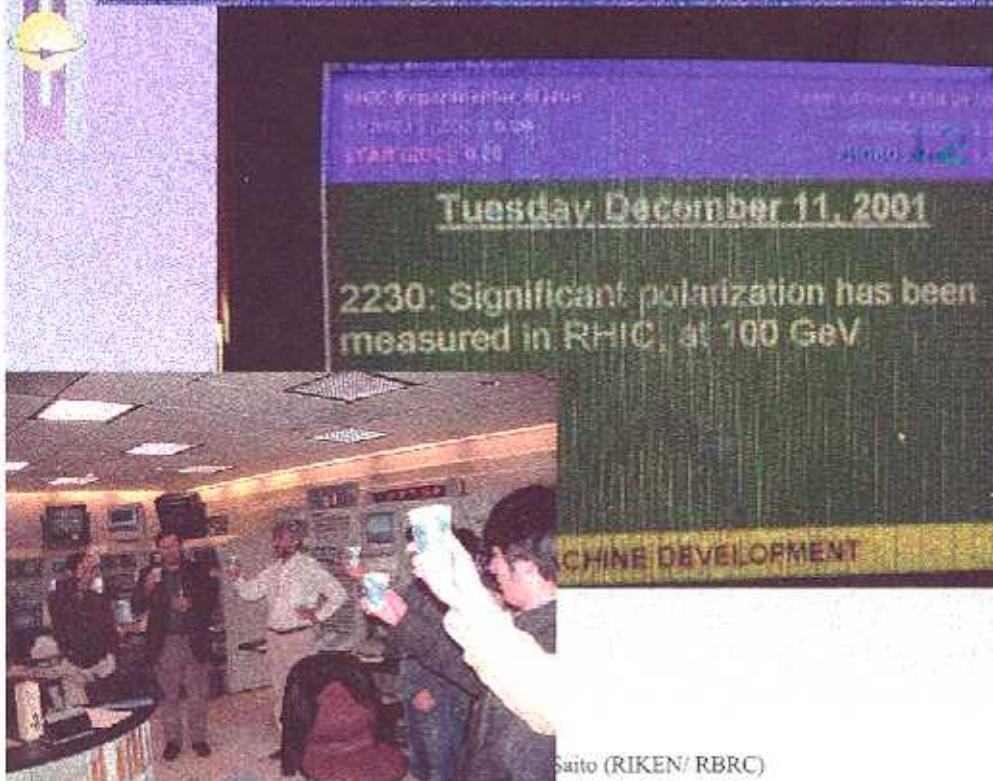
February 22, 2002

Naohito Saito

RIKEN / RIKEN BNL Research Center



The First Polarized pp Collider



Saito (RIKEN/ RBRC)





RHIC Spin Excitement 12/11/01



RHIC Spin Retreat



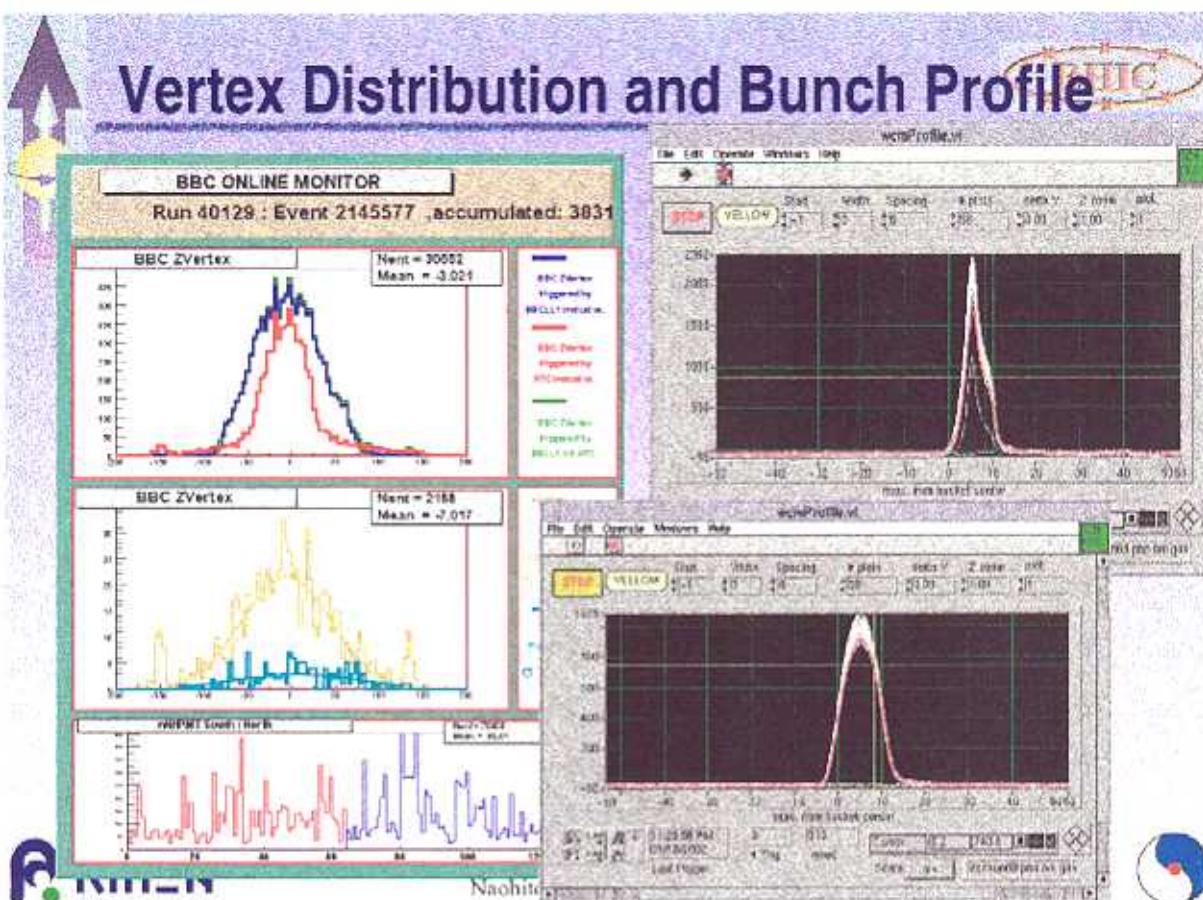
- Questions on Run-2 Performance and Run-3 Plan → Gerry

In Addition, I would add:

- Usefulness of “Gerry’s Meeting”
 - Timely discussion for re-focusing efforts towards most optimal working plan
 - Coherent view among all experiments and all machinists
- Better communication with MCR
 - Polarization Measurement
 - Steering
 - Cog / Re-cog / Spin Flip
 - Scraping
 - Dump
 - Spin Pattern Change
 - Experimental Magnet Control
 - Shift-to-Shift Information transfer among MCR shift crews



Vertex Distribution and Bunch Profile



RHIC Spin Retreat (continued)

- Better Performance and Reproducibility
 - Diagnosis at each step:
 - Source → 200 MeV → Booster → AGS Injection → AGS extraction
→ RHIC injection → RHIC flat top
 - Understand systematics of monitoring system
 - Redundant measurements
 - Multiple measurements at RHIC (cf. Emittance growth ?)
 - E880 vs new AGS Polarimeter
 - RHIC CNI Polarimeter and possible Local Polarimeters
- Commissioning of New Devices and re-commissioning of “OLD” Devices
 - Spin Rotators
 - highly coupled with Local Polarimeters
 - Snakes / Spin Flipper / Polarimeter
 - Source → Linac → Booster → AGS → AtR



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RHIC Spin Retreat (continued)



● Roadmap towards Full-Fledged RHIC Spin Operation

■ Absolute Polarization Calibration

- Pol-J target
- Better calibration at injection energy
- Down ramp

■ Develop Robust Operation Phase space

- Source → Linac → Booster → AGS → RHIC
- Any additional device to achieve this goal?
 - "Strong" AGS Partial Snake

● How can we arrange these developments with minimal interference with Spin and HI PHYSICS program ?



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Agenda (hope still visible...)



Opening Session - March 5 (morning)	Machine Reliability - March 5 (morning)	Machine Experiments and Diagnostics - March 7 AM
8:00-10:10 Welcome: Opening address: Physics goals for the next run: Machine goals for the next run: 10:10-10:40 coffee break	8:30-10:10 Overview and some definitions: Reliability of Tune/Chromaticity/Orbit 10: Reliability of Schedule Correlations in FY01 statistics 10:10-10:40 10:40-11:00	8:00-10:00 Tune and Chromaticity: RHIC Chromaticity Control: Detectors, IPMs, and Trans. Reliability: Longitudinal Compress., Transverse Coherence Monitor, Balancers, IPMs, and Trans. Stability: RF Controls
10:40-11:00 The injectors: The cold run: The proton run: Retreat organization:	10: Summary of system hardware, plans: - Power supplies - Cryo - Quench detection - Controls - Vacuum Reliability of Mainline Physics	10: Transverse Damping: - Instruments - Layout, analysis 10: Beamline Beam Experiments: Transition Crossing Studies: Local Non-linear IR Correlation: Trans. and Longit. Instabilities: beam-beam effects: Polarized Beam Manipulations: Pion source
14:00-15:30 Linear lattice, optics matching: coupling, working point: Chromaticity, mapback, transverse vibrance: Beta squeeze, impact correction/performance: 110 bunches, beam-beam rapping, e- cloud: Au transition crossing, triplet vibration: 15:30-16:00 16:00-17:30 17:30-18:00 18:00-18:30 18:30-19:00 19:00-19:30 19:30-20:00 20:00-20:30 20:30-21:00 21:00-21:30 21:30-22:00 22:00-22:30 22:30-23:00 23:00-23:30 23:30-24:00 24:00-24:30 24:30-25:00 25:00-25:30 25:30-26:00 26:00-26:30 26:30-27:00 27:00-27:30 27:30-28:00 28:00-28:30 28:30-29:00 29:00-29:30 29:30-30:00 30:00-30:30 30:30-31:00 31:00-31:30 31:30-32:00 32:00-32:30 32:30-33:00 33:00-33:30 33:30-34:00 34:00-34:30 34:30-35:00 35:00-35:30 35:30-36:00 36:00-36:30 36:30-37:00 37:00-37:30 37:30-38:00 38:00-38:30 38:30-39:00 39:00-39:30 39:30-40:00 40:00-40:30 40:30-41:00 41:00-41:30 41:30-42:00 42:00-42:30 42:30-43:00 43:00-43:30 43:30-44:00 44:00-44:30 44:30-45:00 45:00-45:30 45:30-46:00 46:00-46:30 46:30-47:00 47:00-47:30 47:30-48:00 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SINGLE TRANSVERSE-SPIN ASYMMETRIES
 A_N AT RHIC

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February 22, 2002

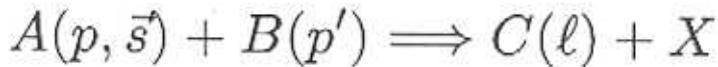
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2. A_N for single hadron production
3. A_N for direct photon
4. A_N for Drell-Yan massive dilepton
5. Summary and outlook

* Some related references: J.Q. and G. Sterman, Phys. Rev. Lett. 67, 2264 (1991); Nucl. Phys. B378, 52 (1992); Phys. Rev. D59, 014004 (1999); D. Boer and J.Q., Phys. Rev. D65, 034008 (2002); C. Kouvaris, J.Q., and W. Vogelsang, in preparation.

1. INTRODUCTION

- Single Spin Process at RHIC:



- only one initial-state hadron is polarized
- observed particle $C(\ell)$ is unpolarized, and can be any high transverse momentum particle π, p, γ , or lepton
- cross section: $\sigma(\ell, \vec{s})$
- Single Spin Asymmetry – definition:
 - Spin-avg X-section: $\sigma(\ell) = \frac{1}{2}[\sigma(\ell, \vec{s}) + \sigma(\ell, -\vec{s})]$
 - Spin-dep X-section:
$$\Delta\sigma(\ell, \vec{s}) = \frac{1}{2}[\sigma(\ell, \vec{s}) - \sigma(\ell, -\vec{s})]$$
 - Single-spin asymmetry:

$$A(\ell, \vec{s}) \equiv \frac{\Delta\sigma(\ell, \vec{s})}{\sigma(\ell)} = \frac{\sigma(\ell, \vec{s}) - \sigma(\ell, -\vec{s})}{\sigma(\ell, \vec{s}) + \sigma(\ell, -\vec{s})}$$

- Single longitudinal-spin asymmetry: A_L
particle spin \vec{s} is parallel to its momentum \vec{p}
- Single transverse-spin asymmetry: A_N
particle spin \vec{s} is perpendicular to its momentum \vec{p}

Even though X-section $\sigma(\ell, \vec{s})$ is finite, single spin asymmetry can vanish due to fundamental symmetries of interactions

- Parity and time-reversal invariance

$$\Rightarrow A_N = 0 \quad \text{for inclusive DIS}$$

- Inclusive DIS X-section:

$$\sigma(\vec{s}_T) \propto L^{\mu\nu} W_{\mu\nu}(\vec{s}_T)$$

- Hadronic tensor:

$$W_{\mu\nu}(\vec{s}_T) \propto \langle P, \vec{s}_T | j_\mu^\dagger(0) j_\nu(y) | P, \vec{s}_T \rangle$$

- Parity and time-reversal invariance:

$$\begin{aligned} & \langle P, \vec{s}_T | j_\mu^\dagger(0) j_\nu(y) | P, \vec{s}_T \rangle \\ &= \langle P, -\vec{s}_T | j_\nu^\dagger(0) j_\mu(y) | P, -\vec{s}_T \rangle \end{aligned}$$

$$\Rightarrow W_{\mu\nu}(\vec{s}_T) = W_{\nu\mu}(-\vec{s}_T)$$

- Spin-dependent X-section:

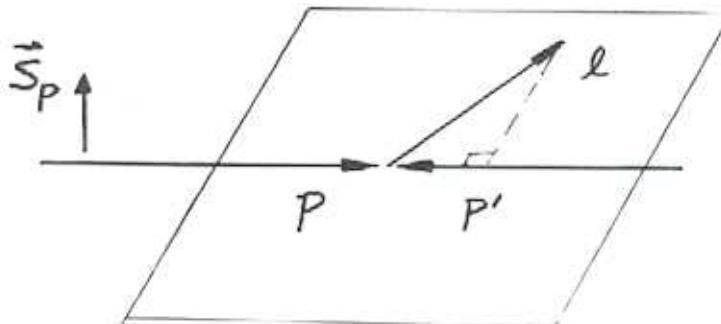
$$\begin{aligned} \Delta\sigma(\vec{s}_T) &\propto L^{\mu\nu} [W_{\mu\nu}(\vec{s}_T) - W_{\mu\nu}(-\vec{s}_T)] \\ &= L^{\mu\nu} [W_{\mu\nu}(\vec{s}_T) - W_{\nu\mu}(\vec{s}_T)] = 0 \end{aligned}$$

because $L^{\mu\nu}$ is symmetric for a unpolarized lepton

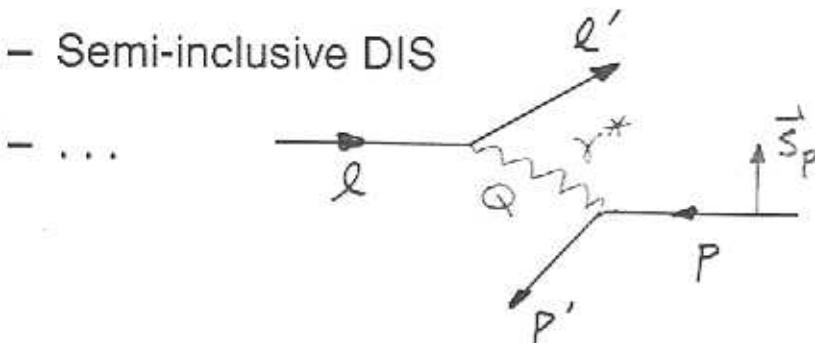
- Above result is valid for any two-current correlators

- Parity conserved interactions $\Rightarrow A_L = 0$

- Single spin asymmetries correspond to T -odd triple product: $A_N \propto i \vec{s}_p \cdot (\vec{p} \times \vec{\ell})$
 - \vec{p} is beam particle's three momentum
 - $\vec{\ell}$ is momentum of observed particle
 - the phase “ i ” is required by time-reversal invariance
 - covariant form: $A_N \propto i \epsilon^{\mu\nu\alpha\beta} p_\mu s_\nu \ell_\alpha p'_\beta$

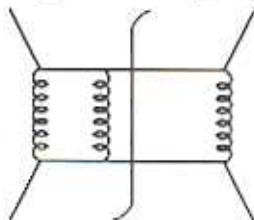


- Nonvanishing A_N requires a phase, a spin flip, and enough vectors to fix a scattering plan
 - Inclusive DIS does not have enough vectors
Note: q and p can only fix a line
- Following examples can generate nonvanishing A_N :
 - Single hadron (or photon) at high ℓ_T
 - Drell-Yan lepton angular distribution
 - Semi-inclusive DIS
 - ...



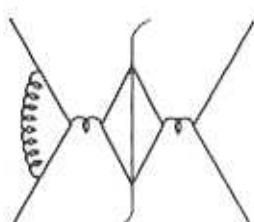
2. A_N FOR SINGLE HADRON PRODUCTION

- pQCD was first used to study single transverse-spin asymmetry by Kane, Pumplin, and Repko in 1978



+ c.c.

– imaginary part of the loop provides the phase



+ c.c.

– quark mass provides the needed spin flip

– $A_N \propto \frac{m_q}{\ell_T} \langle p, \vec{s}_T | \bar{\psi} \Gamma \psi | p, \vec{s}_T \rangle$
where $\Gamma = \gamma^+ \gamma_5 \gamma_T, \dots$

- The fact that $A_N \propto m_q$ indicates that A_N is a twist-3 effect in QCD perturbation theory

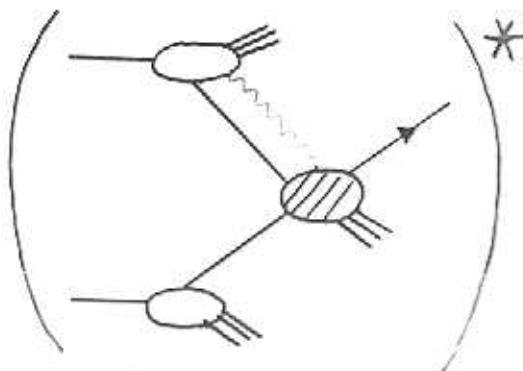
- QCD dynamics is much richer than the parton model

– twist-3 arises from “intrinsic” k_T

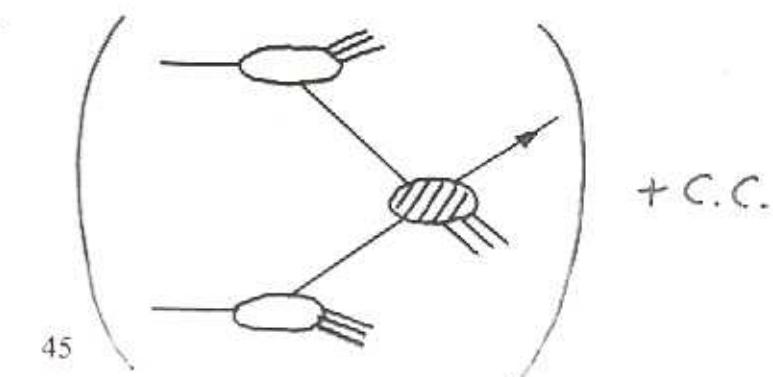
$$\Rightarrow A_N \propto T_{k_T} \sim \langle p, \vec{s}_T | \bar{\psi} \Gamma \partial_T \psi | p, \vec{s}_T \rangle$$

– twist-3 from interference between a quark state and a quark-gluon state

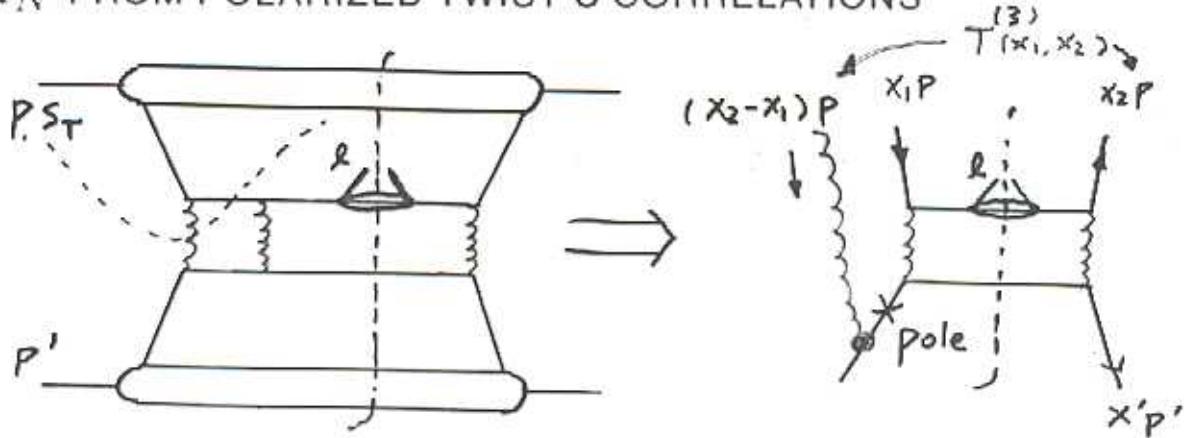
$$\Rightarrow A_N \propto T_{A_T} \sim \langle p, \vec{s}_T | \bar{\psi} \Gamma A_T \psi | p, \vec{s}_T \rangle$$



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A_N FROM POLARIZED TWIST-3 CORRELATIONS



- Unpinched pole $\Rightarrow i\delta(x_1 - x_2)$
- Color gauge invariance combines T_{k_T} and T_{A_T} to

$$T_{D_T}(x_1, x_2) \propto \langle p, \vec{s}_T | \bar{\psi} \Gamma D_T \psi | p, \vec{s}_T \rangle$$

$$T_F(x_1, x_2) \propto \langle p, \vec{s}_T | \bar{\psi} \Gamma F_T^+ \psi | p, \vec{s}_T \rangle$$

- $A_N \neq 0$ requires
 - $T(x_1, x_2, \vec{s}_T) \neq 0$ when $x_1 = x_2$
 - $T(x_1, x_2, \vec{s}_T) \neq T(x_1, x_2, -\vec{s}_T)$
 - Combination of $T(x_1, x_2, \vec{s}_T)$ and partonic part is real
- $\Rightarrow A_N \propto T_F(x_1, x_2)$ with $x_1 = x_2$, and

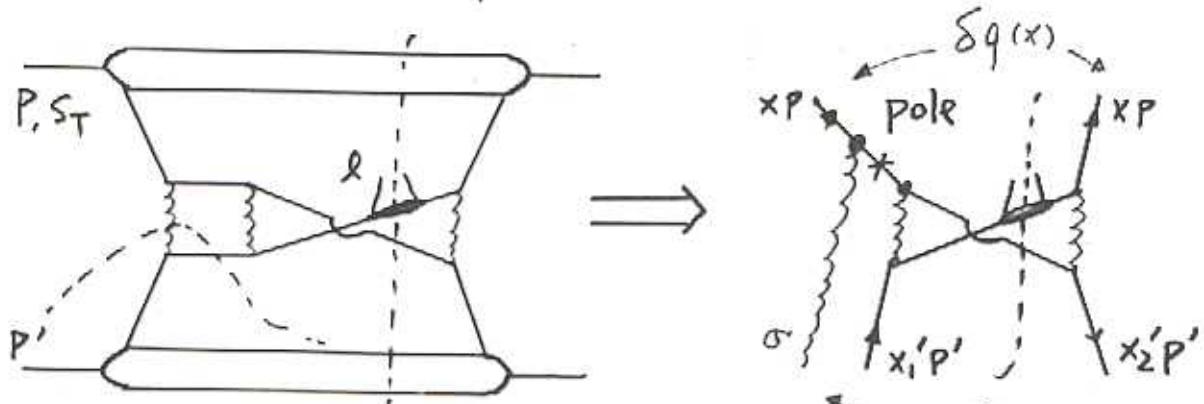
$$T_F(x_1, x_2) = \int \frac{dy_1^- dy_2^-}{4\pi} e^{ix_1 P^+ y_1^- + i(x_2 - x_1) P^+ y_2^-}$$

$$\times \langle P, \vec{s}_T | \bar{\psi}_a(0) \gamma^+ \left[\epsilon^{s_T \sigma n \bar{n}} F_\sigma^+(y_2^-) \right] \psi_a(y_1^-) | P, \vec{s}_T \rangle$$

- Three field operator does not have the probability interpretation of normal parton distributions

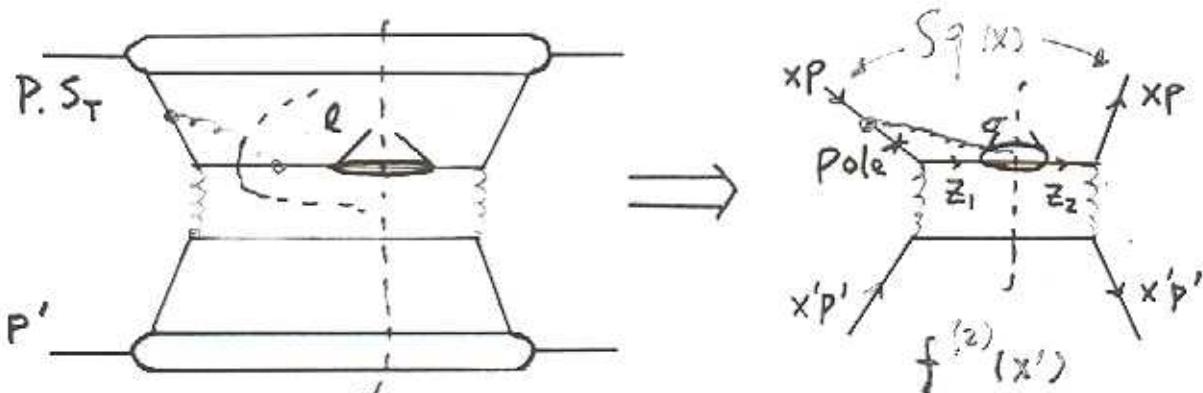
A_N FROM TWIST-2 TRANSVERSITY DISTRIBUTION

- Twist-3 initial-state unpolarized correlation^a



- even γ 's in operator definition of $\delta q(x)$
 \Rightarrow much smaller number of diagrams
- double suppression from $\delta q(x)$ and chiral-odd twist-3 correlation function
- contribution to A_N is a factor of 5-10 smaller than that from polarized initial-state T_F

- Twist-3 unpolarized fragmentation function



- Expect to be of similar size, and much smaller than that from polarized initial-state T_F

^aY. Kanazawa and Y. Koike, Phys. Lett. B490 (2000) 99

FACTORIZABLE SINGLE TRANSVERSE-SPIN ASYMMETRIES

- Generalized factorization formula for hadronic single transverse-spin asymmetries

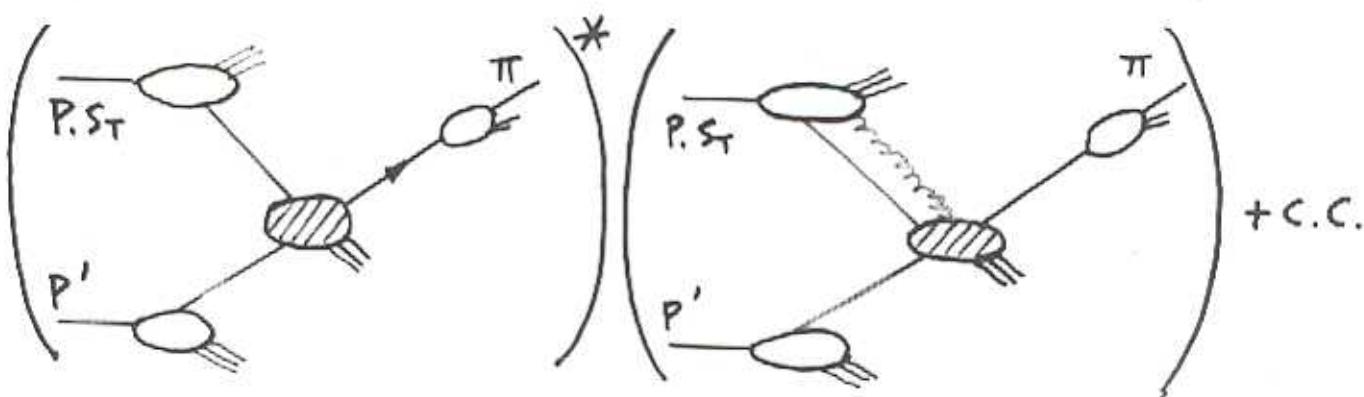
$$\begin{aligned}\Delta\sigma_{AB \rightarrow h}(\vec{s}_T) = & \sum_{abc} T_{a/A}^{(3)}(x_1, x_2, \vec{s}_T) \otimes f_{b/B}(x') \\ & \otimes \hat{\sigma}_{ab \rightarrow c}(\vec{s}_T) \otimes D_{c \rightarrow h}(z) \\ & + \sum_{abc} \delta q_{a/A}^{(2)}(x, \vec{s}_T) \\ & \otimes \left\{ f_{b/B}(x') \otimes \hat{\sigma}'_{ab \rightarrow c}(\vec{s}_T) \otimes D_{c \rightarrow h}^{(3)}(z_1, z_2) \right. \\ & \left. + f_{b/B}^{(3)}(x'_1, x'_2) \otimes \hat{\sigma}''_{ab \rightarrow c}(\vec{s}_T) \otimes D_{c \rightarrow h}(z) \right\}\end{aligned}$$

- $\hat{\sigma}$, $\hat{\sigma}'$, and $\hat{\sigma}''$ are perturbatively calculable
- T, P -invariance \longrightarrow at least one function has TWO x 's
- Chiral-odd $\delta q(x)$ requires chiral-odd $f_{b/B}^{(3)}$ and $D_{c \rightarrow h}^{(3)}$
 \Rightarrow first term is larger than the other two
- Can generalize \otimes to convolution in k_T for both initial-state and final-state interactions
 - Initial-state $k_T \Rightarrow$ Sivers effect
 D. Sivers, Phys. Rev. D43 (91) 261;
 M. Anselmino et al., Phys. Lett. B362 (95) 164; ...
 - Final-state $k_T \Rightarrow$ Collins effect
 J. Collins, Nucl. Phys. B396 (93) 161;
 R.L. Jaffe, et al., Phys. Rev. Lett. 80 (1998) 1166; ...

LEADING CONTRIBUTION TO THE ASYMMETRY OF PION PRODUCTION

- Minimal approach (collinear factorization):

$$\Delta\sigma_{AB \rightarrow h}(\vec{s}_T) \approx \sum_{abc} T_{a/A}^{(3)}(x_1, x_2, \vec{s}_T) \otimes f_{b/B}(x') \otimes \hat{\sigma}_{ab \rightarrow c}(\vec{s}_T) \otimes D_{c \rightarrow h}(z)$$

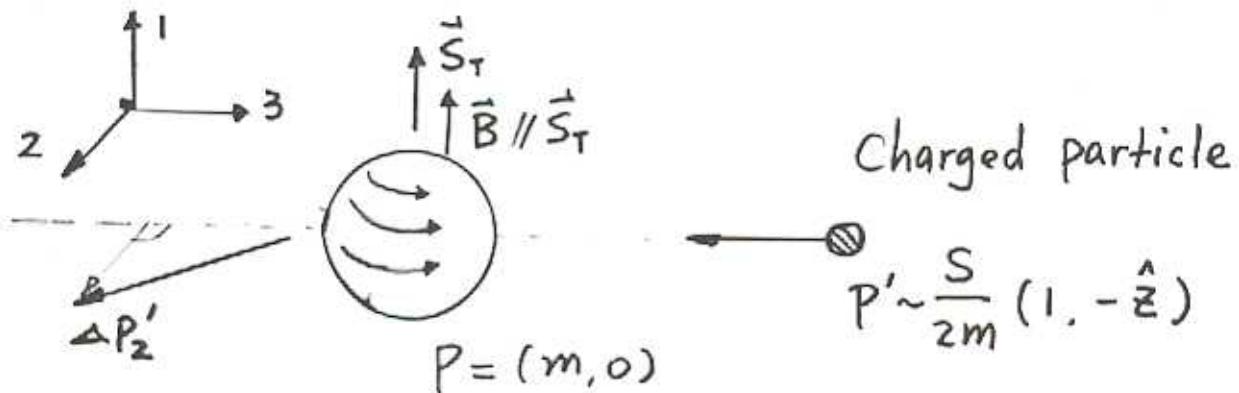


- Keep only quark fragmentation
 - observed momentum: $\ell_T^2 \propto xx'z^2S$
 - parton distributions are steeply falling as $x \rightarrow 1$
e.g., $f_q(x) \propto (1-x)^\alpha$ with $\alpha > 3 - 4$
 - quark fragmentation function falls slower as $z \rightarrow 1$
e.g., $D_{q \rightarrow \pi}(z) \propto (1-z)^{n_q}$ with $n_q \sim 2$
 \Rightarrow
X-section is dominated by small $x \sim x'$ and large z
- Need gluon fragmentation contribution at low ℓ_T and large S

WHAT $T_F(x, x)$ TELLS US?

$$T_F(x, x) \propto \langle P, \vec{s}_T | \bar{\psi}_a(0) \gamma^+ \left[\int dy_2^- \epsilon^{s_T \sigma n \bar{n}} F_\sigma^+(y_2^-) \right] \psi_a(y_1^-) | P, \vec{s}_T \rangle$$

- a classical (Abelian) analog:
rest frame of (p, \vec{s}_T)



- change of transverse momentum

$$\frac{d}{dt} p'_2 = e(\vec{v}' \times \vec{B})_2 = -ev_3 B_1 = ev_3 F_{23}$$

- in the c.m. frame

$$(m, \vec{0}) \rightarrow \bar{n} = (1, 0, 0_T), \quad (1, -\hat{z}) \rightarrow n = (0, 1, 0_T)$$

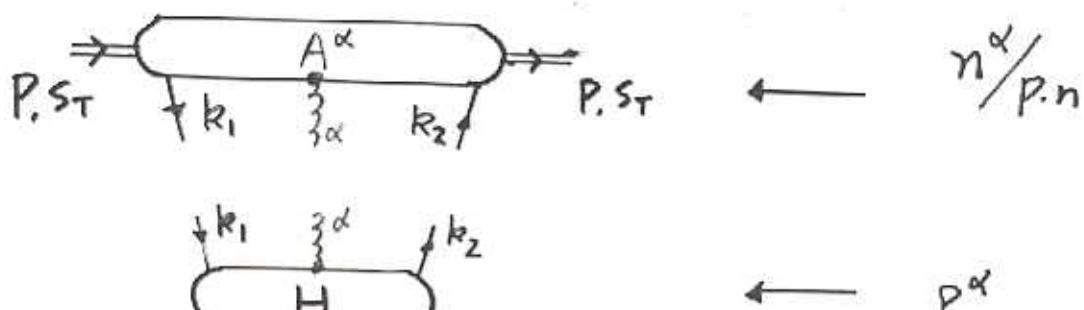
$$\implies \frac{d}{dt} p'_2 = e \epsilon^{s_T \sigma n \bar{n}} F_\sigma^+$$

- total change: $\Delta p'_2 = e \int dy^- \epsilon^{s_T \sigma n \bar{n}} F_\sigma^+(y^-)$

- Color field strength $F^{+\sigma}$ alone is not gauge invariant
- T_F represents a fundamental quantum correlation between quark and gluon inside a hadron

TECHNICAL STEPS TO CALCULATE THE ASYMMETRIES

— in a color covariant gauge



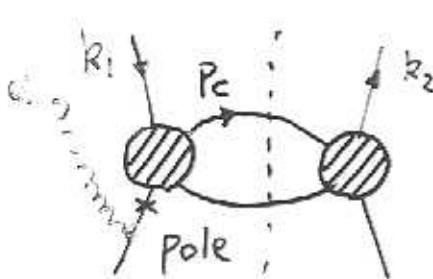
- gluon field: $A^\alpha \rightarrow n \cdot A = A^+$
- expand $H(k_1, k_2)$ to linear in k_T

$$H(k_1, k_2) \rightarrow H(x_1 p, x_2 p) + \frac{\partial H}{\partial k_{2\sigma}} (k_{2T} - k_{1T})^\sigma + \dots$$

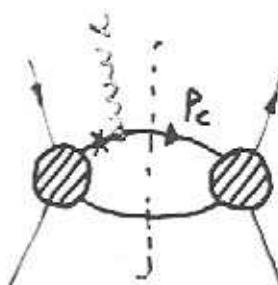
- convert $(k_{2T} - k_{1T})^\sigma A^+ \rightarrow \partial^\sigma A^+ \rightarrow F^\sigma +$
- factorized formula:

$$\Delta\sigma(\vec{s}_T) = \int dx_1 dx_2 T_F(x_1, x_2) \left[i \epsilon^{\sigma s_T n \bar{n}} \frac{\partial H}{\partial k_{2\sigma}} \right]_{k_{2T}=0}$$

- either x_1 or x_2 is fixed by the pole in partonic part.



Initial-state



Final-state

CONTRIBUTION FROM INITIAL-STATE INTERACTION

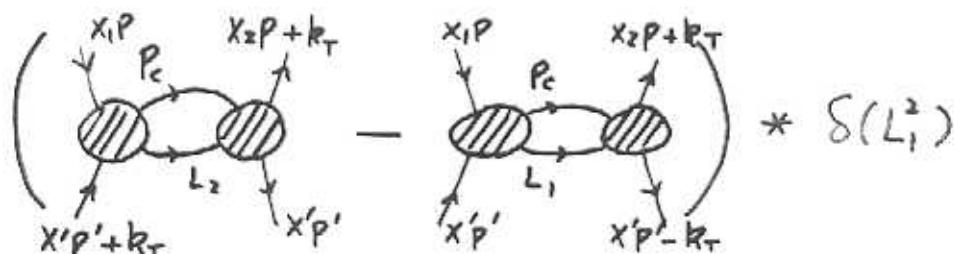
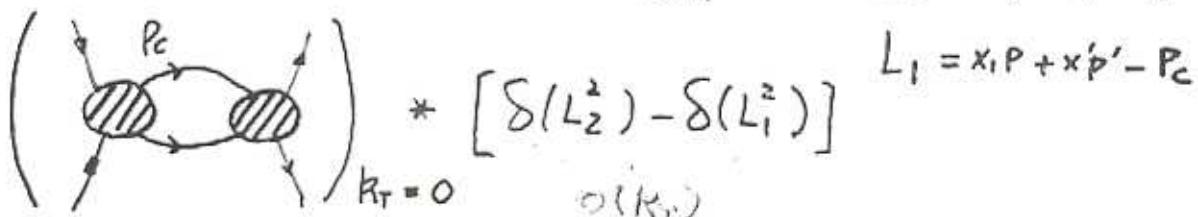
$$H(x_1, x_2, k_T) \propto \frac{(x_2 - x_1)p + k_T}{\delta(L_2^2)} + \frac{x_2 p + k_T}{\delta(L_1^2)}$$

- Soft-gluon pole gives the needed phase:

$$\frac{1}{x_2 - x_1 + i\epsilon} \rightarrow -i\pi\delta(x_2 - x_1)$$

- Two type contributions to partonic $\frac{\partial H}{\partial k_T}$:

$$L_2 = x_2 P + x' P' - P_c + k_T$$



- phase space δ -functions \Rightarrow derivative term

$$\delta(L_2^2) - \delta(L_1^2) \approx \delta'(L_1^2)(-2p_c \cdot k_T) \Rightarrow x \frac{d}{dx} T_F(x, x)$$

– non-derivative term

$$(L) - (R) \propto \frac{2p_C \cdot kT}{\hat{u}} \Rightarrow T_F(x, x)$$

- in forward region, $x \frac{d}{dx} T_F(x, x) \gg T_F(x, x)$
because $T_F(x, x) \propto (1-x)^\alpha$ as $x \rightarrow 1$.

CONTRIBUTION FROM FINAL-STATE INTERACTION

$$H(x_1, x_2, k_T) \propto \frac{x_1 P}{L_2} + \frac{x_2 P + k_T}{L_1} + \delta(L_2^2) + \delta(L_1^2)$$

- Soft-gluon pole gives the needed phase:

$$\frac{-1}{x_2 - x_1 + \frac{p_c \cdot k_T}{p_c \cdot p} - i\epsilon} \rightarrow -i\pi\delta(x_2 - x_1 + \frac{p_c \cdot k_T}{p_c \cdot p})$$

- Two type contributions to partonic $\frac{\partial H}{\partial k_T}$:

$$\left(\begin{array}{c} P_C \\ \text{shaded circle} \end{array} \right)_{k_T=0} * \left[\underbrace{\delta(L_2^z) - \delta(L_1^z)}_{O(k_T)} \right]$$

$$\left(\begin{array}{c} P_c - k_T \\ \text{---} \\ P_c + k_T \end{array} \right) * \delta(L_1^2)$$

- phase space δ -functions \Rightarrow derivative term

$$\delta(L_2^2) - \delta(L_1^2) \approx \delta'(L_1^2)(-2p_c \cdot k_T) \Rightarrow x \frac{d}{dx} T_F(x, x)$$

- non-derivative term

$$(L) - (R) \propto \left[\frac{2p_C \cdot kT}{\hat{u}} + \frac{2p_C \cdot kT}{\hat{t}} \right] \Rightarrow T_F(x, x)$$

- most contribution to $A_N \propto \ell_T/u$

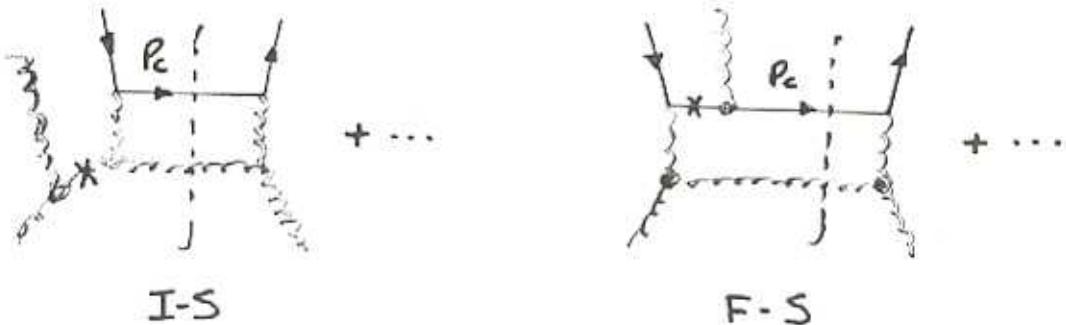
- part of final-state effect $\propto \ell_T/t \sim 1/\ell_T$

$\Rightarrow A_N$ does not fall as fast as $1/\ell_T$ as ℓ_T increases.

Leading $(\partial/\partial x)T_F(x, x)$ contribution to the asymmetries

$$E \frac{d\Delta\sigma}{d^3\ell} \propto \epsilon^{\ell_T s_T n \bar{n}} D_{c \rightarrow \pi}(z) \otimes \left[-x \frac{\partial}{\partial x} T_F(x, x) \right] \\ \otimes \frac{1}{-\hat{u}} \left[G(x') \otimes \Delta\hat{\sigma}_{qg \rightarrow c} + \sum_{q'} q'(x') \otimes \Delta\hat{\sigma}_{qq' \rightarrow c} \right]$$

- $\Delta\hat{\sigma}_{qg \rightarrow c}$ and $\Delta\hat{\sigma}_{qq' \rightarrow c}$ are perturbatively calculable
- Example, $qg \rightarrow qg$ scattering



- initial-state:

$$\frac{1}{2(N_C^2 - 1)} \left[-\frac{\hat{s}}{\hat{u}} - \frac{\hat{u}}{\hat{s}} \right] \left[1 - N_C^2 \frac{\hat{u}^2}{\hat{t}^2} \right]$$

- final state:

$$\frac{1}{2N_C^2(N_C^2 - 1)} \left[-\frac{\hat{s}}{\hat{u}} - \frac{\hat{u}}{\hat{s}} \right] \left[1 + 2N_C^2 \frac{\hat{s}\hat{u}}{\hat{t}^2} \right]$$

- unpolarized:

$$\frac{N_C^2 - 1}{2N_C^2} \left[-\frac{\hat{s}}{\hat{u}} - \frac{\hat{u}}{\hat{s}} \right] \left[1 - \frac{2N_C^2}{N_C^2 - 1} \frac{\hat{s}\hat{u}}{\hat{t}^2} \right]$$

- extra gluon interaction leads to a different color factor

MODEL FOR QUARK-GLUON CORRELATION $T_F(x, x)$

- Twist-3 correlation $T_F(x, x)$:

$$T_F(x, x) = \int \frac{dy_1^-}{4\pi} e^{ixP^+y_1^-} \times \langle P, \vec{s}_T | \bar{\psi}_a(0) \gamma^+ \left[\int dy_2^- e^{s_T \sigma^n \bar{n}} F_\sigma^+(y_2^-) \right] \psi_a(y_1^-) | P, \vec{s}_T \rangle$$

- Twist-2 quark distribution:

$$q(x) = \int \frac{dy_1^-}{4\pi} e^{ixP^+y_1^-} \langle P, \vec{s}_T | \bar{\psi}_a(0) \gamma^+ \psi_a(y_1^-) | P, \vec{s}_T \rangle$$

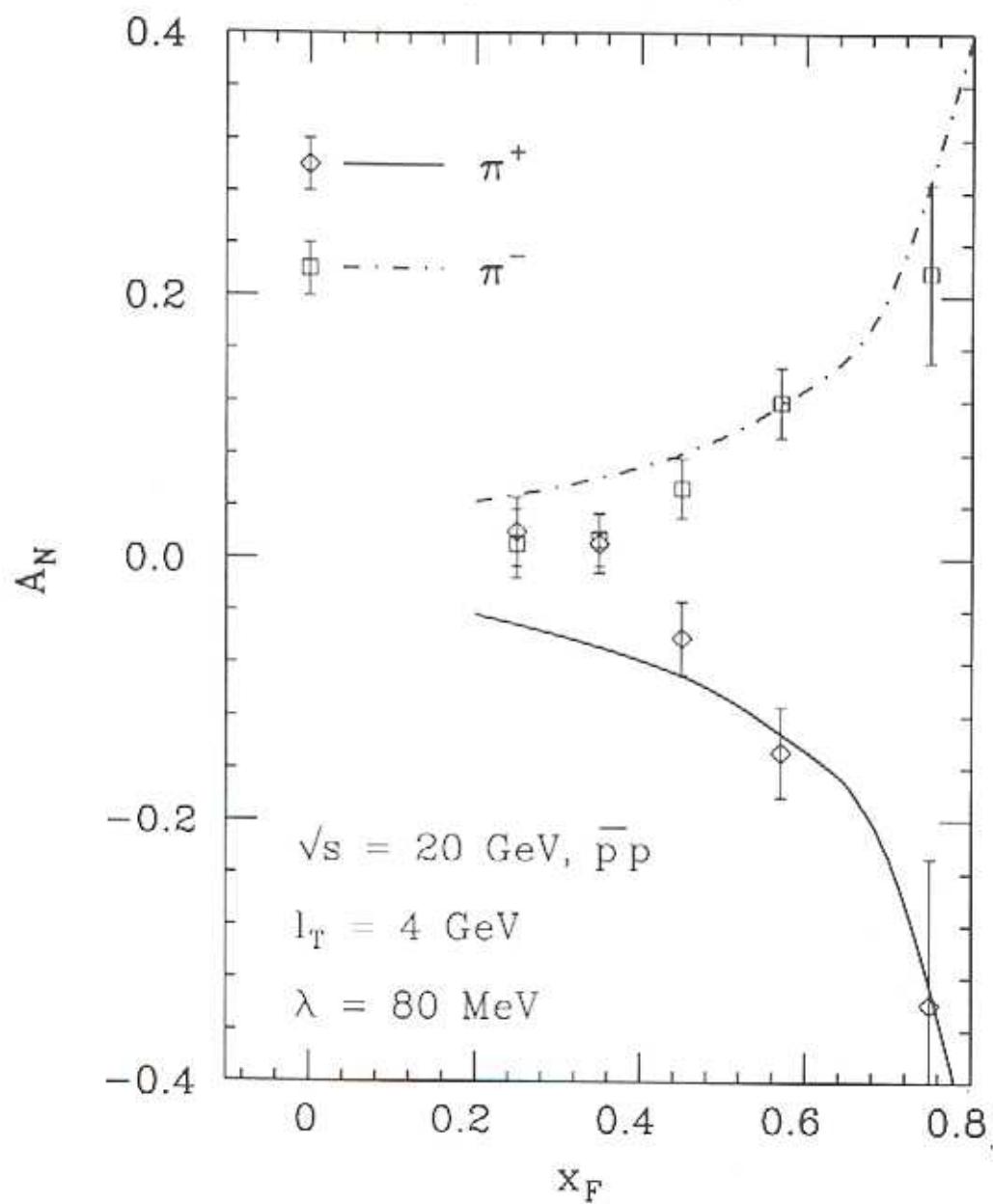
- Model for $T_F(x, x)$ of quark flavor a :

$$T_{F_a}(x, x) \equiv \kappa_a \lambda q_a(x)$$

with $\kappa_u = +1$ and $\kappa_d = -1$ for proton

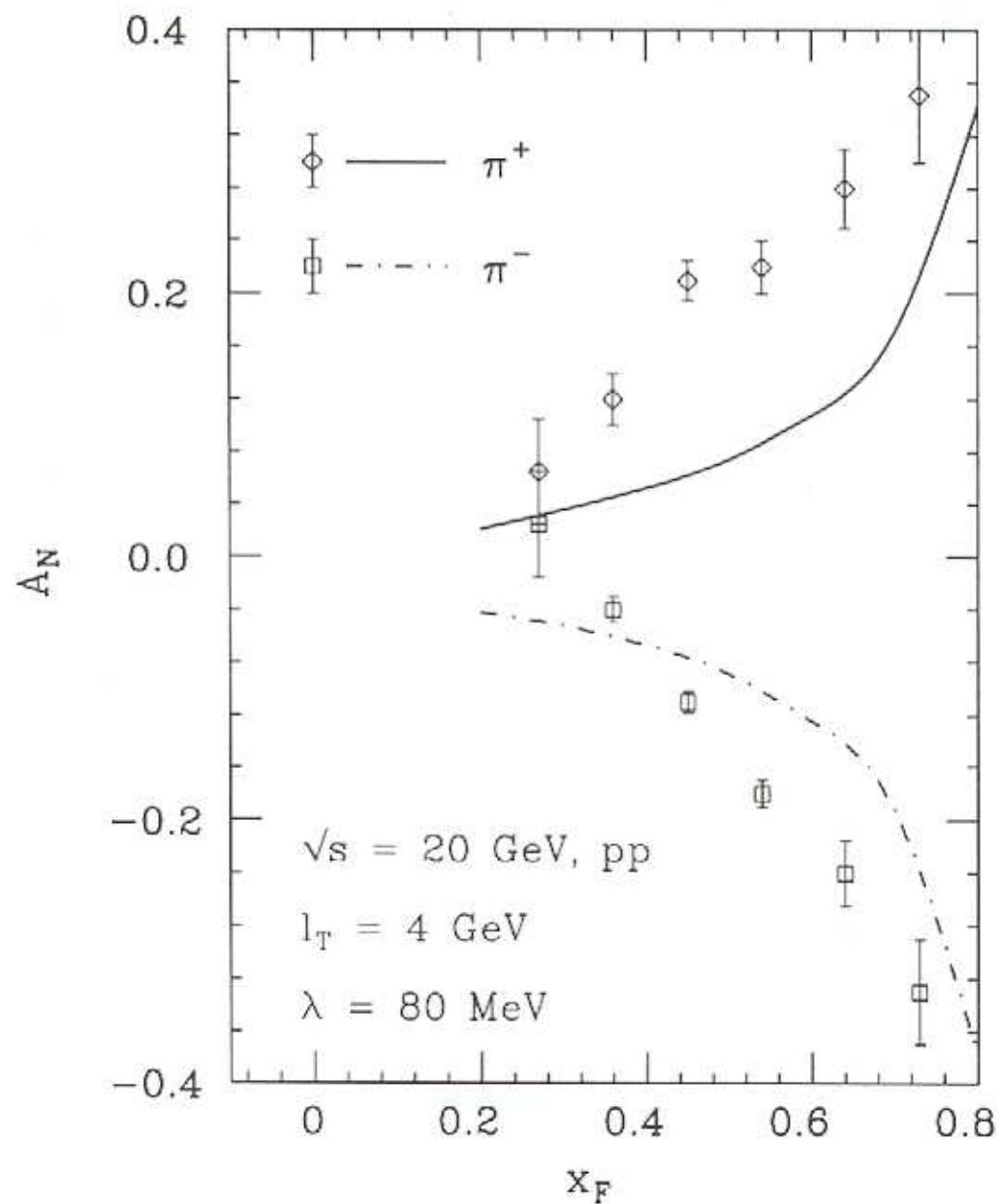
- Fitting parameter $\lambda \sim O(\Lambda_{\text{QCD}})$
- Predictive power of the factorization approach:
 - extract $T_F(x, x)$ from one observable, say π^+ or π^-
 - use it to predict other observable, say π^0
 - $(\partial/\partial x)T_F(x, x)$ leads to enhancement of the asymmetries in forward region
 - same partonic parts can be used for calculating the asymmetries in production of other types of single hadron, say in k , or p production

COMPARE AN APPLE WITH AN ORANGE (I)



Fermilab data with ℓ_T up to 1.5 GeV

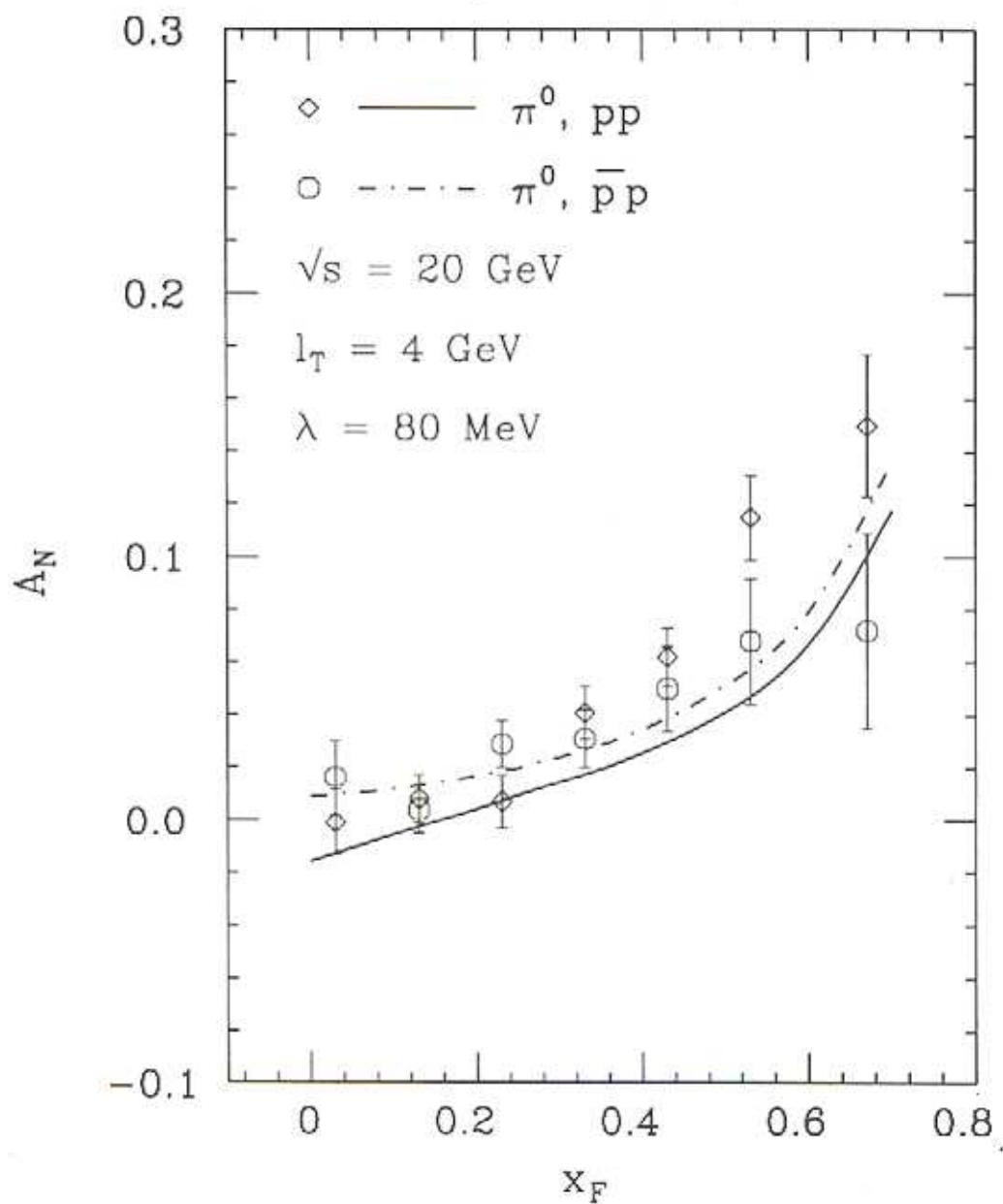
COMPARE AN APPLE WITH AN ORANGE (II)



Fermilab data with ℓ_T up to 1.5 GeV

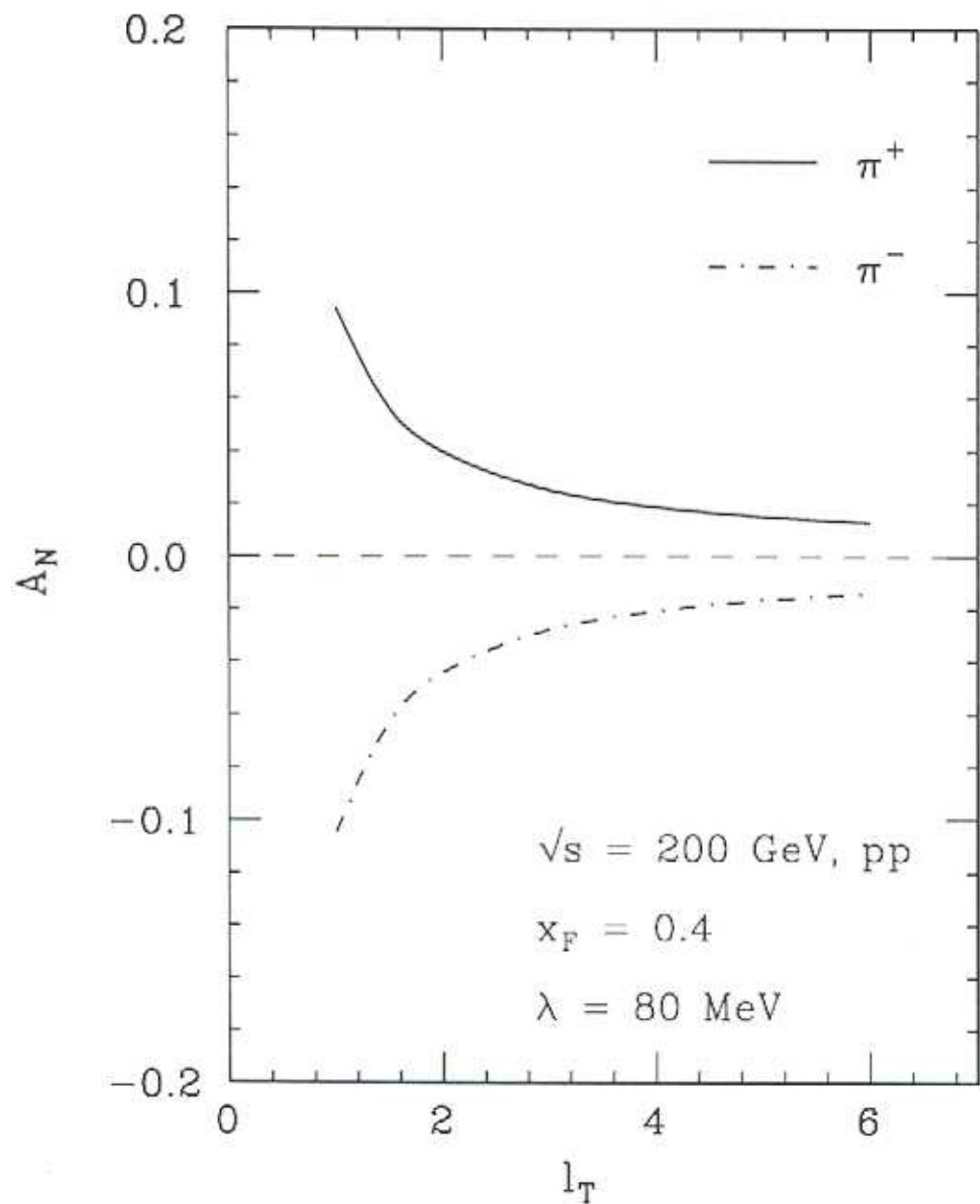
Theory curves fit data better if evaluated at a lower ℓ_T

COMPARE AN APPLE WITH AN ORANGE (III)



Fermilab data with ℓ_T up to 1.5 GeV

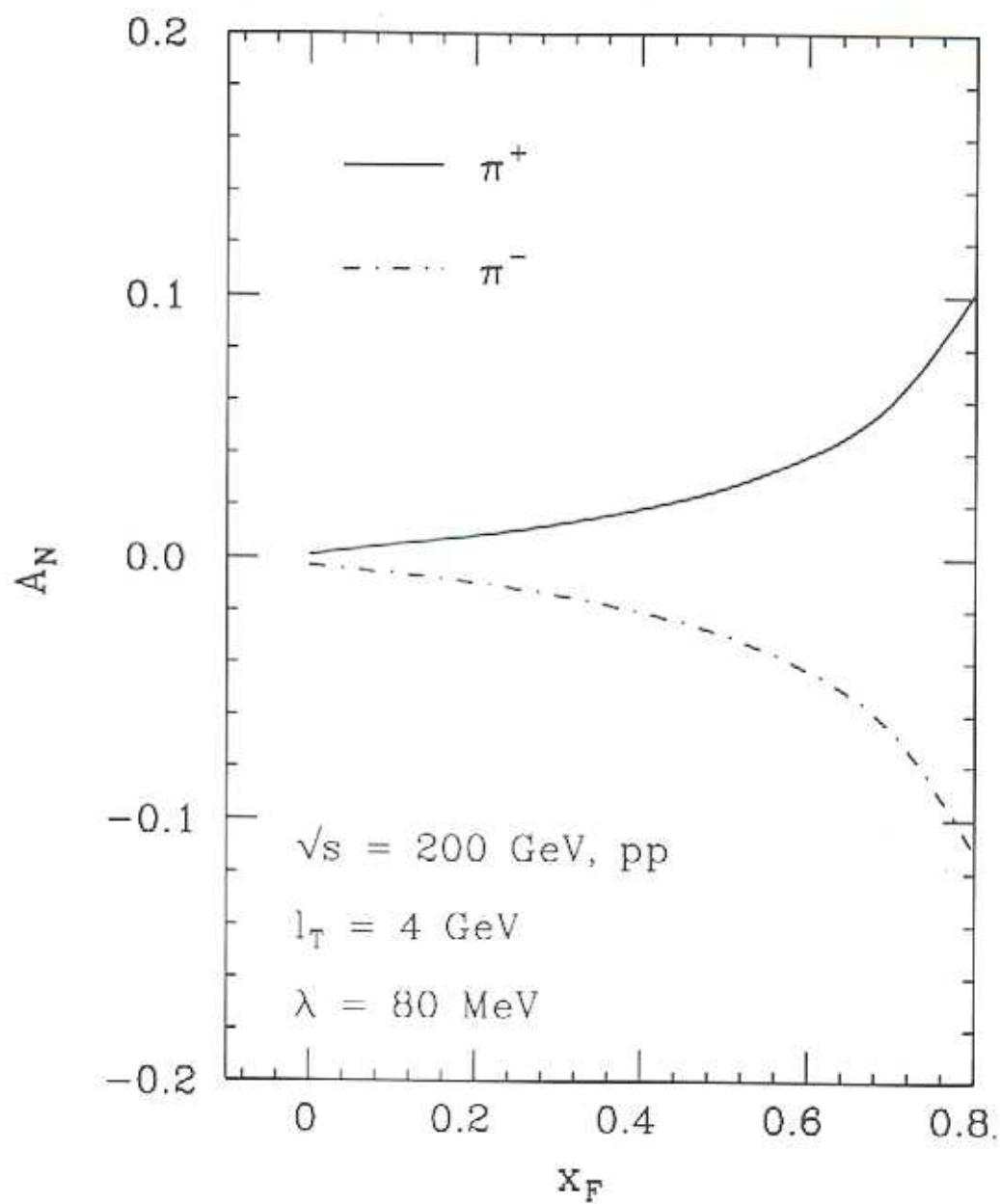
A_N AT RHIC ENERGY (I)



Derivative term only for partonic hard part

Non-derivative term are getting calculated by Kouvaris, Qiu, and Vogelsang

A_N AT RHIC ENERGY (II)



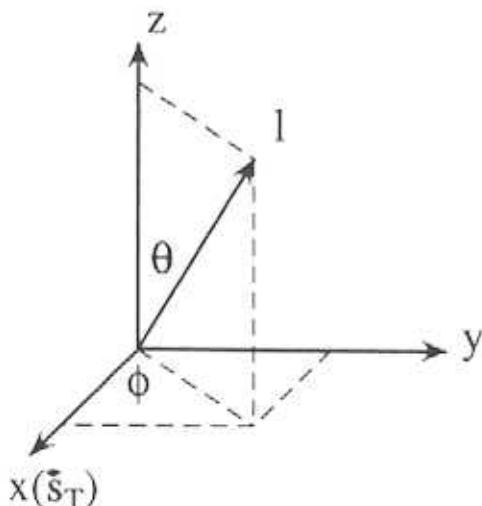
Derivative term only for partonic hard part

4. A_N FOR DRELL-YAN MASSIVE DILEPTON^a

- Process:

$$A(p, \vec{s}) + B(p') \Rightarrow \gamma^*(Q) [\rightarrow \ell\bar{\ell}] + X$$

- Frame:



- Single transverse-spin asymmetry in $\frac{d\sigma}{dQ^2 d\Omega}$

$$A_N = \sqrt{4\pi\alpha_s} \left[\frac{\sin 2\theta \sin \phi}{1 + \cos^2 \theta} \right] \frac{1}{Q} \times \frac{\sum_q e_q^2 \int dx T_q(x, x) \bar{q}(Q^2/xS)}{\sum_q e_q^2 \int dx q(x) \bar{q}(Q^2/xS)}$$

- No derivative term at the tree level!
- In principle, there is no free parameter!
- A_N is very small and is estimated to be 2-4%

^aD. Boer and J.Q., Phys. Rev. D65 (2002) 034008, and references therein.

5. SUMMARY AND OUTLOOK

- Single transverse-spin asymmetry is a unique tool to explore nonperturbative physics beyond parton distributions
- QCD factorization approach allows to quantify the size of high order corrections, because of infrared safe partonic hard parts
- QCD factorization approach provides a systematic way to calculate the asymmetries in different processes
- Single transverse spin asymmetry in single hadron production is an excellent observable to test the QCD factorization
- Data on the asymmetries provide nonperturbative information on quark-gluon correlation
- Theoretical calculation with derivative term only are consistent with Fermilab data
- A full leading order calculation will soon be available.
- Drell-Yan single transverse-spin asymmetry is a clean probe. But, the asymmetry is small